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Reliability Modeling of Standby and Emergency Generating Systems

A Report by

J. Michael Lynch

Submitted to

Electrical Engineering Department

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Master of Engineering

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Reliability Modeling of Standby and Emergency Generating Systems

A Report by

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ABSTRACT

Engine-generator units for use in standby power systems are reviewed. Reliability models including state transition diagrams are developed for sample systems. Methods of reliability analysis are discussed and the calculation of useful reliability measures is demonstrated. A computer program for the solution of reliability measures is included. Example systems studies are conducted and results presented.

ACKNOWLEDGEMENT

I have greatly appreciated the interest and dedication displayed by all the faculty and staff of the Electrical Engineering Department. I wish to express my sincerest thank you to Dr. Chanan Singh for his exceptional patience, understanding, and guidance provided to me on this project.

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I. INTRODUCTION

The inevitable failure of electrical power networks - due to factors even outside the system manager's control, such as events of nature and early wear out of components - dictates the necessity for stand-by and emergency power generation system to support critical loads. Many factors can influence the requirements or specifications for such a system, but most stem from an evaluation of the user's needs. Such factors include whether or not life threatening or hazard/safety situations are involved, whether plant or property damage could occur, whether a significant loss in revenue from operations could occur, the cost of back-up equipment, and the reliability of the normal power source. This paper looks at the engine-driver generator system as an emergency or standby source and investigates a method for modeling the integrated/standby system for the purpose of obtaining useful reliability information.

Discussion within the paper begins by looking at typical engine-generator systems, followed by a presentation of techniques for evaluating reliability measures on such systems. Reliability models and state transition diagrams are then created for example engine-generator configurations. Finally, selected parameters within the models are varied in order to observe their effect upon the reliability indices and the results are presented.

II. ENGINE-GENERATOR CONFIGURATION

Reference [1] discusses many arrangements for emergency and standby generation systems. Several different types of energy conversion hardware are available including gas and diesel engines, gas and steam turbines, mechanical stored energy systems, and battery storage and uninterruptible

power supplies. A typical engine-generator configuration is shown here in Figure 1. The dotted lines show how the system can be expanded to a multi-engine configuration. There are many advantages to installing several units of lower capacity than a single large capacity unit. Besides the increased reliability, which shall be shown later, maintenance and repairs can be conducted without loss of adequate backup, additional less critical loads can be supported in the event of power loss while providing the necessary degree of reliability for the critical loads, peak load showing can be performed with extra generating capacity, and future expansion is facilitated by installation of similar units. Of course the advantages must be balanced against the costs of installing a more complex system as well as the length of time the generators might be expected to operate on a continuous basis - larger generators being more suited to longer operating periods.

Operation of the system in Figure 1 is assumed to be fully automatic. When the normal source fails, all engines in the system are automatically started. The first engine to reach operating voltage and frequency causes the emergency load to transfer to the generator. Other engines are paralled and switched on-line to share the load. If sufficient capacity is available, other less critical loads can then also be transferred to the generators. In the event a generator should fail, appropriate load shedding automatically occurs. Regularaly scheduled inspections and preventive maintenance are assumed to take place.

An important matter to bear in mind when considering the application of a standby/emergency system is to ensure loads are compatible with the monetary interruptions and transients associated with the transfer between power sources. Lighting and other resistive loads are highly

tolerant of breaks and large transients, whereas transients lasting on the order of micro-seconds could be disastrous to data processing and comunications hardware -important information or critical program execution and memory could be lost. Special consideration must also be given to highly inductive loads and associated motor control circuitry.

II. COMPONENT FAILURE MODES AND DATA COLLECTION

Before delving into reliability models and measures, a brief discussion on statistical data collection is in order. The collection of information concerning equipment failures - the time of failure, time to repair, severity, and cause of failure, etc. - is the foundation upon which all quantitative reliability analysis rests. The statistics generated from this data in the form of mean durations, failure and repair rates, probabilities, etc. are the basic quantities used in the modeling process. Reference [2] presents several discussions which highlight the importance of accurate data collection as well as describes several established and fledgling data reports and analysis systems. The engineer in the field plays a vital role in supporting these systems by ensuring accurate and timely maintenance and repair data are reported.

When adequate data bases are not available, more subjective techniques such as failure modes, effects, and criticality analysis must be employed. Significant system components are enumerated and the modes or manner in which the component's failure affects the system are listed. A subjective ordering of importance of this list in accordance with some applicable criteria (life-safety, endurance, cost, etc.) can be followed by non-parametric statistical techniques to provide rudimentary quantitative data. A listing of component failure modes can also be helpful in creating

the framework for a data collection and analysis system capable of providing accurate statistics for more complex quantitative reliability models; an example of this could be a model which distinguishes the difference between long and short term failures, with respective frequencies, yielding reliability indices more accurate than results from a lumped average model.

IV. RELIABILITY EVALUATION

A. BASIC TERMS AND INTRODUCTION

To effectively perform reliability studies, it is helpful for the analyst to possess a working knowledge of probability theory and portions of statistical methodology. Reference [3] provides a useful introduction to these topics and employs many examples directly applicable to power system studies. Given this background, a few additional terms and definitions are required before an analysis can be undertaken. Reference [4] has compiled many of the commonly used reliability terms; pertinent trms and indices for this paper are presented here.

Failure Rate - mean number of failures per unit exposure time of a component.

Unavailability - the steady state probability that a system will be in a failed state or out of service for scheduled maintenance, etc. This is the long run fraction of time spent in the failed state.

Frequency of System Failure - mean number of system failures per unit time.

Mean Down Time - expected or long-term average duration of a single failure unit.

Mean Cycle Time - expected time between successive failures.

Mean Up Time - expected time of stay in the up state in one cycle.

B. METHODS OF SOLUTION

There are several well-established techniques for the solution of system reliability indices. Chief amongst these are: network techniques including network reduction and the minimal cut set approach, useful when a system can be represented as a collection of series and/or parallel components; decomposition by conditional probability, a manner of reducing a complicated system into simple subsystems whose reliability indices can be figured separately and combined with the remaining subsystems; and the state space approach, in which a system can be represented by a collection of states, each of which completely describes the conditions under which the system is operating, e.g. components up, components down, the given environment, etc. The state space approach is considered ideal for the solution of the standby/emergency generator problem since the system states can be quickly enumerated and interdependencies associated with component failures or environmental transitions can be readily accomodated.

C. STATE SPACE APPROACH

Use of the state space approach for the solution of system reliability indices requires four primary steps as developed in Reference [5] and shown as follows:

1. Identify all system states - typically, components can be operating or failed, or a particular environmental condition can be in effect.

2. Determine interestate transition rates - the mean number of occurrences, per unit time, in which the system undergoes the change or transition represented between state i and state j. This figure is a key statistic obtained from the field data collection process. An important assumption made here, which is necessary for the subsequent analysis, is that the length of stay in a given state, considered to be a random variable, possesses an exponential probability distribution. The prime consequence of which is that the interstate transition rates are constant.
3. Computer state probabilities - the probability of the system being in state i. Here, the concept of statistical independence comes into play. If a component is allowed to undergo any one of its possible transitions out of a given state without being influenced by the condition of the remaining components within the system, or the prevailing environment, then it is considered independent of the other components and the environment. When all components are independent, then the determination of the state probability becomes a simple matter of computing the product of the component probabilities for their respective conditions. If, however, there is statistical dependence amongst the components, e.g. no other components may fail after one has failed, or upon the environment, then a set of simultaneous linear equations must be solved. This set of equations stems from the theory of continuous Markov processes (see Reference [3]); this is where the constant transition rate assumption is necessary.

Reference [6] presents an efficient matrix algorithm for the computation of state probabilities for this situation:

$$BP = C \tag{1}$$

B = matrix obtained from A by replacing all elements of an arbitrarily selected row K by 1;

A = matrix of transition rates such that element

$a_{ij} = \lambda_{ji}$ and $a_{ii} = -\sum_{j, j \neq i} a_{ji}$;

λ_{ij} = constant transition rate from state i to j;

P = column vector of steady state system state probabilities;

C = column vector with Kth element equal to 1 and other elements set to zero.

4. Calculate reliability indices - Reference [6] provides convenient formulas for calculation of the most commonly used reliability measures:

(a) system unavailability - the summation of probabilities of the state representing system failure,

$$P_f = \sum_{i \in F} p_i \tag{2}$$

where P_f = probability of system failure,

F = subset of failed states,

p_i = probability for state i;

(b) frequency of system failure -

$$f_f = \sum_{i \in (S-F)} p_i \sum_{j \in F} \lambda_{ij} , \tag{3}$$

$$= \sum_{i \in F} p_i \sum_{j \in (S-F)} \lambda_{ij} , \tag{4}$$

where f_f = frequency of system failure,

S = system state space;

(c) mean cycle time -

$$T_f = 1/f_f \quad ; \quad f_f - (fi) \tag{5}$$

(d) mean down time - the expected time of stay in F in one cycle is

$$d_f = P_{f}/f_f \; ; \tag{6}$$

(e) mean up time - the expected time of stay in up states (S-F) is

$$du = T_f - d_f \; . \tag{7}$$

It should be noted that the above procedure for calculating the probabilities and indices was based on steady-state analysis. Time dependent solution in the form of coupled differential equations is also possible, albeit more complex, should transient analysis be required. As may have been observed, and experience bears out, the state space appraoch can become an unwieldly process for large interdependent systems. It proves, though, to be an ideal technique for the standby/emergency generator problem.

V. RELIABILITY MODELS FOR THE EMERGENCY/STANDBY GENERATOR SYSTEM

The procedure for evaluating reliability measures will be demonstrated through the use of two separate models. Reference [6] developed a simplified reliability model for a combined normal and standby/emergency power source. The first model presented here is an expansion on that system. The second model used in this paper is developed for a dual generator standby configuration. Both of these models are based on

the engine generator configuration shown in Figure 1. In addition, these models shall also account for a two-state weather environment. Figures 2 and 3 are the state transition diagrams for these systems.

In the diagrams, all the possible system states have been enumerated. Each state represents the following conditions:

a) Normal source -

NG = Normal Good
NF = Normal Failed

b) Standby generator(s) -

1. single generator case
   SG = Standby Good
   SF = Standby Failed

   Distinction is also made as to whether the standby failed on start-up or subsequently while running under load.

2. dual generator case
   G = generator(s) Good (either one or both)
   FR = generator(s) Failed while Running
   FS = generator(s) Failed on Start-up

c) Environment or weather state -

Environment #1 = Normal Weather
Environment #2 = Inclement (or Stormy) Weather

The interstate rates represented on the diagrams are as follows:

λp, μp = Failure and repair rates for normal source
λs = Failure of standby generator
μss = repair rate of standby generator for start-up failure
μsr = repair rate of standby generator for running failure
ω_{12}, ω_{21} = transition rates between environments

Unprimed rates denote values for normal weather state, primed rates denote values for inclement weather state. With the distinction of start and running failures, the probability of starting the standby source when needed must be accounted for by the coefficient α. The probability of a failure on start-up is the complementary coefficient: $\bar{\alpha} = 1 - \alpha$.

Some important assumptions must be mentioned regarding the state transition diagrams:

1) The probability of two failures and/or repairs occuring simultaneously is considered negligible. Hence, each interstate transition represents only a single event.
2) All repairs are considered to be independent, i.e. if the normal and/or one or more generators have failed, repairs progress simultaneously and respond according to their respective transition rates.
3) Generator fuel supplies are considered inexhaustible, thus lack of fuel is not counted as failure.

Treatment of Two-State Environments

References [5] and [7] discuss a method for evaluating reliability measures under fluctuating environments. The key to understanding this technique is in recognizing the interdepencies created between the duration of stay in an environment and the component transition rates within that environment. The following relations can be used to obtain values for transition rates within a given environment.

$$\lambda AV = \lambda[N/(N+S)] + \lambda' \; [S/(N+S)] \tag{8}$$

$$\lambda' S/(\lambda N + \lambda' S) = \chi \tag{9}$$

where

λAV = average failure rate
λ = failure rate within environment #1
λ' = failure rate within environment #2
N = length of stay in environment #1
S = length of stay in environment #2
χ = fraction of total number of failures occurring in environment #2

Equation (8) relates the average or equivalent failure rate (typically available from data collection activities) to the respective failure rates within each environment, each being multiplied by the fraction of time the system stays within that environment. Equation (9) is just a manner of representing the fraction of total failures which occur in environment #2. The transition rates between environments are found by inverting the lengths os stay within the environments:

$\omega_{12} = \frac{1}{N}$ = Transition rate from environment one to two;

$\omega_{21} = \frac{1}{S}$ = Transition rate from environment two to one.

This assumes that the durations of the environments are exponentially distributed, thus allowing constant transition rates. For the standby generation system models developed in this section, it has also been assumed that the repair rates for all components are unaffected by the fluctuating environment.

It should be mentioned that the above treatment of a two-state environment can be used for many different types of environments. Besides weather conditions, other environments such as variable corrosive conditions, dust conditions, or electromagnetic field conditions could also be considered.

VI. EXAMPLE SYSTEM STUDIES

For the transition diagrams of Figures (2) and (3), reliability indices will be obtained by computer solution in a manner which allows variation of selected parameters (rates or probabilities) in order to observe their effects upon the system.

A. SAMPLE DATA

The sample data used in Reference [6] for the engine-generator system will be used in these studies. For the normal source, the failure rate and mean down times are

$\lambda P(AV) = 0.537/\text{year}$

MDT_P = mean down time

= 5.66 hours

Note: The reciprocal of MDT_P is μ_P, thus $\mu_P = \frac{1}{MDT_P} = 1548.76325/\text{year}$.

For each engine generator

$\lambda_{S(AV)} = 0.00536/\text{year}$

$MDT_S = 478$ hours

$\mu SR = 18.33891/\text{year}$

From reference [5], typical values for the mean durations of each environment are

mean duration environment #1, N = 200 hours

mean duration environment #2, S = 1.5 hours

Thus,

$\omega_{12} = 43.830/\text{year}$

$\omega_{21} = 5844.0/\text{year}$

B. PARAMETER STUDIES AND PROGRAMMED SOLUTION

The program used for solution of the sample systems is provided in the appendix. A series of four studies were conducted on both the single engine and dual engine .

The series of tests were repeated for the generator systems in three separate environmental configurations. The three environmental configurations were: a) one state environment - no fluctuating weather conditions considered; b) two-state weather environment with the fraction of failures in the stormy state, $\chi = 0.20$; and c) two-state weather environment, $\chi = 0.80$. The series of four studies included the following:

1) Fix μ_{SS} equal to μ_{SR} and vary $\bar{\alpha}$ from 0.02 to 0.10;
2) Fix $\bar{\alpha}$ equal to 0.01 and vary μ_{SS} from μ_{SR} to $2\mu_{SR}$;
3) Repeat (2) with $\bar{\alpha} = 0.05$;
4) Repeat (2) with $\bar{\alpha} = 0.10$.

For the two-state environment configurations, the average failure rates were broken down as follows:

= 0.20	= 0.80
$\lambda_P = 0.43282/yr$	$\lambda_P = 0.10821/yr$
$\lambda_{P'} = 14.4274/yr$	$\lambda_{P'} = 57.70960/yr$
$\lambda_S = 0.00432/yr$	$\lambda_S = 0.00108/yr$
$\lambda_{S'} = 0.14401/yr$	$\lambda_{S'} = 0.57602/yr$

C. RESULTS

Results of the system studies are presented in Tables 1-8. Each table contains the results of one of the generator systems in all three environmental situations. The following observations and conclusions can be drawn from these results.

1. In the case of the single generator/single state system, with $\mu_{SS} = \mu_{SR}$ the results are identical to those obtained for the simplified engine-generator model of Reference [6].

2. The most significant improvements seen in the reliability indices come as a result of introducing the redundancy of the dual generator system. Improvement over the single generator system appears, though, to be dependent upon the value of $\bar{\alpha}$. As $\bar{\alpha}$ increases, the degree of improvement becomes less. At $\bar{\alpha} = 0.01$ there is a factor of 100 improvement over the single engine system, while at $\bar{\alpha} = 0.05$ a factor of only 20 exists and at $\bar{\alpha} = 0.10$ a factor of only 10 exists.
3. In all situtations, the indices are found to suffer as $\bar{\alpha}$ is increased. For the single generator system, the increase in expected down time per year and failure frequency over the range of $\bar{\alpha}$ is approximately an order of magnitude, while the indices vary two order of magnitude for the dual generator system. The variation for the dual generator system appears to be the square of the variation for the single generator system.
4. The variation of μ_{SS} over its range resulted in only small effect on the reliability indices for all configurations. Although slight, the change was noted always as an improvement in the indices as the value of μ_{SS} increased.
5. Introduction of the weather states also has only a limited effect on the indices. There is mixed results as to whether improvement on degradation of the indices occurs. It appears that $\bar{\alpha}$ plays a role in defining a threshhold at which the two-state environments show improvement of the indices over the single state environment. For the single engine system,

improvement is noted for $\bar{\alpha} > 0.01$. For the dual generator system, improvement occurs for $\bar{\alpha} > 0.05$. The change in the value of χ does not alter these trends, but does increase the magnitude of the difference.

VII. CONCLUSION

This paper has discussed the engine-generator in the role of a standby/emergency power system. The state space approach for evaluating important reliability measures can be quickly and efficiently applied to varied standby/emergency configurations. The results of such a quantitative evaluation can assist in making cost vs. benefit decisions for an installation as well as making comparisons of generator systems. The example studies conducted in the paper demonstrated the improved reliability measures obtained by introducing redundancy into a standby configuration, but another important aspect to consider is that of the start-up failure probability. Results showed that a single engine system with high start-up probability stands to be as equally reliable as a dual generator configuration with lower start-up probability. Consideration of environmental conditions can also have an effect on reliability measures but on a far more restricted scale.

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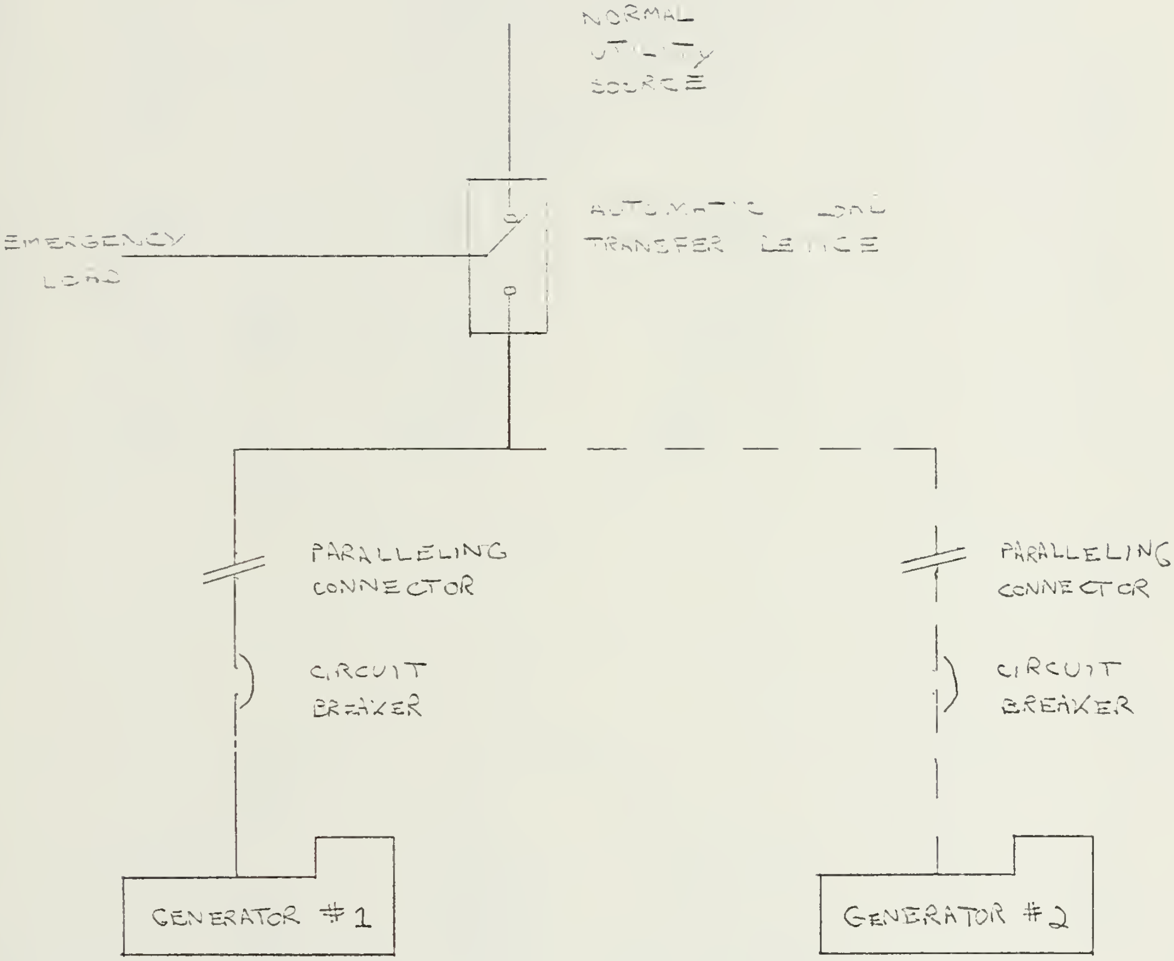

FIGURE 1. TYPICAL STANDBY - EMERGENCY SYSTEM USING ENGINE - GENERATOR (REF 1)

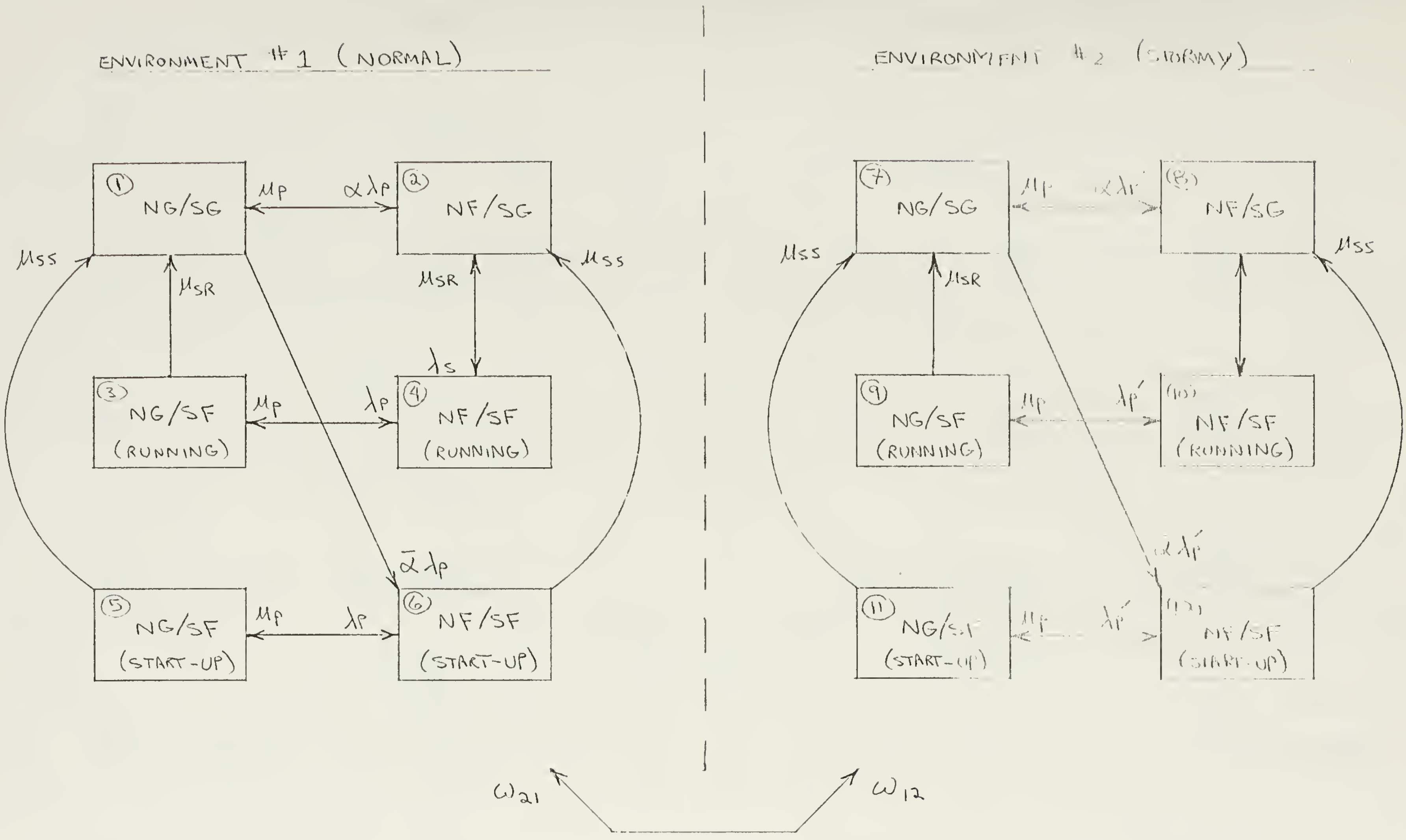

FIGURE 2. STATE TRANSITION DIAGRAM FOR SINGLE ENGINE STANDBY SYSTEM IN TWO-STATE ENVIRONMENT

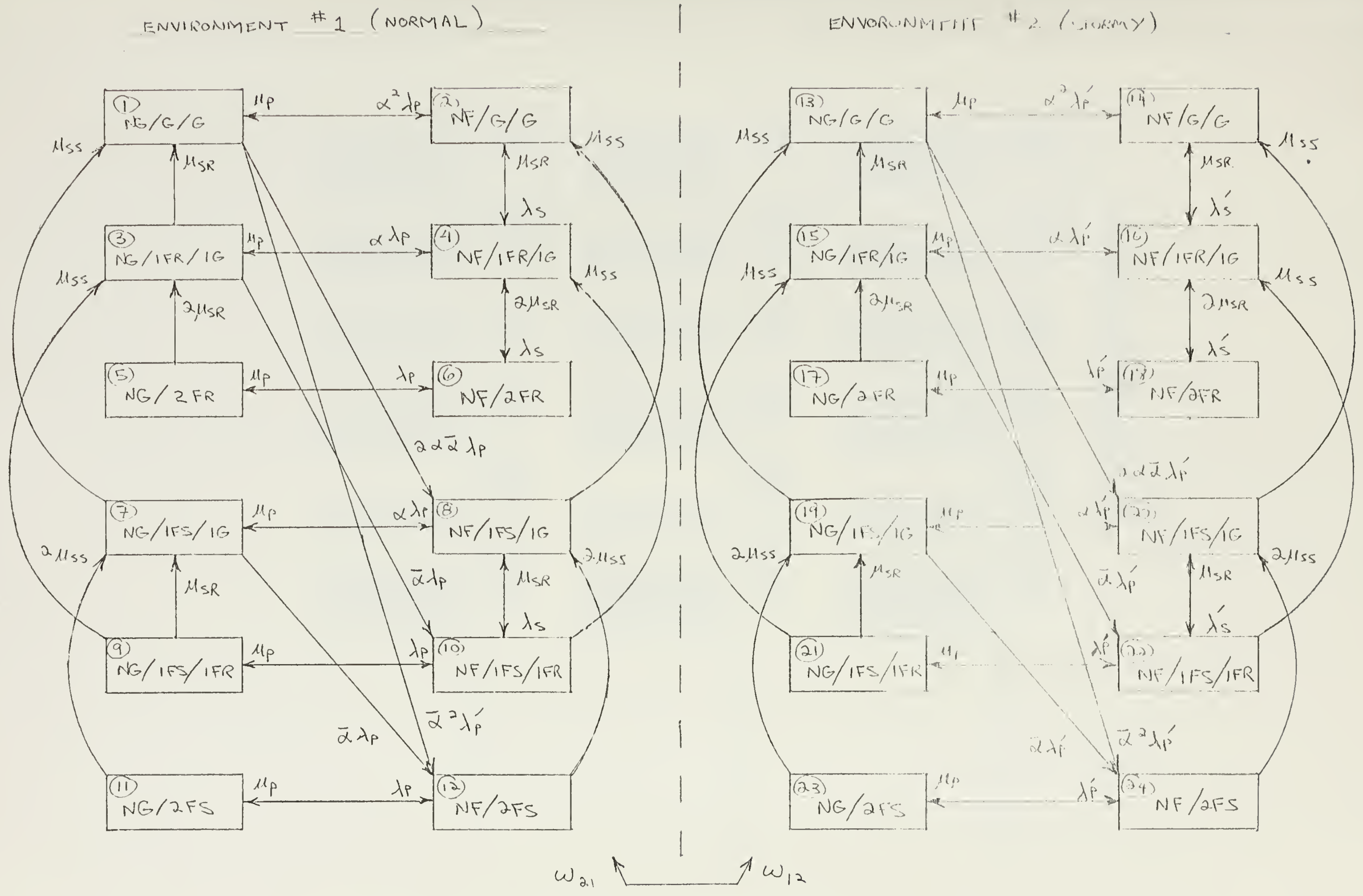

FIGURE 3. STATE DIAGRAM FOR DUAL ENGINE-GENERATOR IN TWO-STATE ENVIRONMENT

TABLE 1. SOLUTION OF RELIABILITY INDICES FOR SINGLE GENERATOR
mu(ss) FIXED @ 18.33891, ALPHA VARIED

ONE STATE ENVIRONMENT

TEST PARAMETER ALPHA	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
0.010000	0.030898	0.005524	181.03709	5.594	181.03645
0.020000	0.061768	0.011042	90.56039	5.594	90.55975
0.030000	0.092620	0.016558	60.39453	5.594	60.39389
0.040000	0.123455	0.022070	45.31030	5.594	45.30966
0.050000	0.154271	0.027579	36.25934	5.594	36.25870
0.060000	0.185070	0.033085	30.22519	5.594	30.22456
0.070000	0.215850	0.038588	25.91500	5.594	25.91437
0.080000	0.246613	0.044087	22.68232	5.594	22.68168
0.090000	0.277359	0.049584	20.16797	5.594	20.16734
0.100000	0.308086	0.055077	18.15648	5.594	18.15585

TWO-STATE ENVIRONMENT. x = 0.20

TEST PARAMETER ALPHA	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
0.010000	0.030901	0.005524	181.02392	5.594	181.02328
0.020000	0.061762	0.011041	90.57022	5.594	90.56958
0.030000	0.092605	0.016555	60.40478	5.594	60.40414
0.040000	0.123430	0.022066	45.31938	5.594	45.31875
0.050000	0.154237	0.027573	36.26730	5.594	36.26666
0.060000	0.185027	0.033077	30.23222	5.594	30.23158
0.070000	0.215798	0.038578	25.92127	5.594	25.92063
0.080000	0.246552	0.044076	22.68796	5.594	22.68733
0.090000	0.277288	0.049571	20.17312	5.594	20.17248
0.100000	0.308006	0.055062	18.16120	5.594	18.16056

TWO-STATE ENVIRONMENT: x = 0.80

TEST PARAMETER ALPHA	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
0.010000	0.030939	0.005531	180.80253	5.594	180.80190
0.020000	0.061660	0.011023	90.72011	5.594	90.71947
0.030000	0.092362	0.016512	60.56347	5.594	60.56283
0.040000	0.123046	0.021997	45.46082	5.594	45.46018
0.050000	0.153711	0.027479	36.39142	5.594	36.39078
0.060000	0.184358	0.032958	30.34191	5.594	30.34127
0.070000	0.214986	0.038433	26.01923	5.594	26.01859
0.080000	0.245595	0.043905	22.77634	5.594	22.77571
0.090000	0.276186	0.049374	20.25358	5.594	20.25295
0.100000	0.306759	0.054839	18.23505	5.594	18.23441

TABLE 2. SOLUTION OF RELIABILITY INDICES FOR DUAL GENERATOR
mu(ss) = 18.33391, alpha VARIED

ONE STATE ENVIRONMENT

TEST PARAMETER alpha	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
0.010000	0.000319	0.000058	17364.45213	5.529	17364.45150
0.020000	0.001272	0.000230	4346.24561	5.529	4346.24498
0.030000	0.002860	0.000517	1933.50802	5.529	1933.50739
0.040000	0.005079	0.000919	1088.57170	5.529	1088.57107
0.050000	0.007929	0.001434	697.29171	5.529	697.29108
0.060000	0.011408	0.002063	484.64456	5.529	484.64393
0.070000	0.015515	0.002806	356.36663	5.529	356.36600
0.080000	0.020248	0.003662	273.07213	5.529	273.07150
0.090000	0.025605	0.004631	215.94052	5.529	215.93989
0.100000	0.031584	0.005712	175.05676	5.529	175.05613

TWO-STATE ENVIRONMENT: x = 0.20

TEST PARAMETER alpha	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
0.010000	0.000319	0.000058	17354.35471	5.529	17354.35408
0.020000	0.001272	0.000230	4345.27835	5.529	4345.27772
0.030000	0.002860	0.000517	1933.31334	5.529	1933.31271
0.040000	0.005079	0.000919	1088.53021	5.529	1088.52958
0.050000	0.007929	0.001434	697.29223	5.529	697.29160
0.060000	0.011408	0.002063	484.65798	5.529	484.65735
0.070000	0.015514	0.002806	356.38369	5.529	356.38306
0.080000	0.020246	0.003662	273.08956	5.529	273.08893
0.090000	0.025603	0.004631	215.95713	5.529	215.95649
0.100000	0.031582	0.005712	175.07216	5.529	175.07153

TWO-STATE ENVIRONMENT: x = 0.80

TEST PARAMETER alpha	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
0.010000	0.000322	0.000058	17193.77563	5.529	17193.77500
0.020000	0.001277	0.000231	4329.65876	5.529	4329.65813
0.030000	0.002865	0.000518	1930.09830	5.529	1930.09767
0.040000	0.005083	0.000919	1087.80185	5.529	1087.80122
0.050000	0.007930	0.001434	697.25629	5.529	697.25566
0.060000	0.011404	0.002063	484.84096	5.529	484.84033
0.070000	0.015504	0.002804	356.63270	5.529	356.63207
0.080000	0.020227	0.003658	273.34959	5.529	273.34896
0.090000	0.025573	0.004625	216.20773	5.529	216.20710
0.100000	0.031539	0.005704	175.30623	5.529	175.30560

TABLE 3. SOLUTION OF RELIABILITY INDICES FOR SINGLE GENERATOR

alpha = 0.01 mu(ss) varied

ONE STATE ENVIRONMENT:

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.030898	0.005524	181.03709	5.594	181.03645
20.172801	0.030783	0.005510	181.50145	5.587	181.50081
22.006692	0.030682	0.005498	181.89025	5.581	181.88961
23.840583	0.030590	0.005488	182.22054	5.574	182.21991
25.674474	0.030507	0.005479	182.50460	5.568	182.50397
27.508365	0.030431	0.005472	182.75151	5.561	182.75087
29.342256	0.030359	0.005465	182.96809	5.555	182.96746
31.176147	0.030292	0.005460	183.15962	5.548	183.15899
33.010038	0.030229	0.005455	183.33020	5.542	183.32957
34.843929	0.030169	0.005450	183.48309	5.535	183.48246
36.677820	0.030111	0.005446	183.62090	5.529	183.62027

TWO-STATE ENVIRONMENT: x = 0.20

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.030901	0.005524	181.02392	5.594	181.02328
20.172801	0.030786	0.005510	181.48788	5.587	181.48724
22.006692	0.030684	0.005498	181.87634	5.581	181.87571
23.840583	0.030593	0.005488	182.20635	5.574	182.20571
25.674474	0.030510	0.005480	182.49017	5.568	182.48953
27.508365	0.030433	0.005472	182.73686	5.561	182.73623
29.342256	0.030362	0.005466	182.95326	5.555	182.95263
31.176147	0.030295	0.005460	183.14462	5.548	183.14399
33.010038	0.030232	0.005455	183.31506	5.542	183.31443
34.843929	0.030172	0.005451	183.46782	5.536	183.46719
36.677820	0.030114	0.005446	183.60552	5.529	183.60489

TWO-STATE ENVIRONMENT: x = 0.80

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.030939	0.005531	180.80253	5.594	180.80190
20.172801	0.030825	0.005517	181.26017	5.587	181.25953
22.006692	0.030724	0.005505	181.64334	5.581	181.64270
23.840583	0.030633	0.005495	181.96885	5.574	181.96821
25.674474	0.030551	0.005487	182.24881	5.568	182.24818
27.508365	0.030475	0.005480	182.49216	5.561	182.49153
29.342256	0.030404	0.005473	182.70564	5.555	182.70501
31.176147	0.030338	0.005468	182.89443	5.549	182.89380
33.010038	0.030275	0.005463	183.06259	5.542	183.06196
34.843929	0.030215	0.005458	183.21332	5.536	183.21269
36.677820	0.030158	0.005454	183.34920	5.529	183.34857

TABLE 4. SOLUTION OF RELIABILITY INDICES FOR DUAL GENERATOR
alpha = 0.01 mu(ss) VARIED

ONE STATE ENVIRONMENT:

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.000318	0.000058	17364.45213	5.529	17364.45150
20.172801	0.000316	0.000057	17473.78461	5.516	17473.78398
22.006692	0.000313	0.000057	17565.78154	5.504	17565.78091
23.840583	0.000311	0.000057	17644.26247	5.491	17644.26185
25.674474	0.000309	0.000056	17712.00162	5.478	17712.00099
27.508365	0.000308	0.000056	17771.06259	5.466	17771.06196
29.342256	0.000306	0.000056	17823.01243	5.453	17823.01181
31.176147	0.000304	0.000056	17869.06217	5.441	17869.06154
33.010038	0.000303	0.000056	17910.16265	5.429	17910.16203
34.843929	0.000302	0.000056	17947.07087	5.416	17947.07025
36.677820	0.000301	0.000056	17980.39697	5.404	17980.39635

TWO-STATE ENVIRONMENT: x = 0.20

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.000319	0.000058	17354.35471	5.529	17354.35408
20.172801	0.000316	0.000057	17463.53553	5.516	17463.53490
22.006692	0.000313	0.000057	17555.40565	5.504	17555.40502
23.840583	0.000311	0.000057	17633.77980	5.491	17633.77917
25.674474	0.000309	0.000056	17701.42755	5.478	17701.42692
27.508365	0.000308	0.000056	17760.40972	5.466	17760.40910
29.342256	0.000306	0.000056	17812.29138	5.453	17812.29076
31.176147	0.000305	0.000056	17858.28112	5.441	17858.28050
33.010038	0.000303	0.000056	17899.32907	5.429	17899.32845
34.843929	0.000302	0.000056	17936.19081	5.416	17936.19019
36.677820	0.000301	0.000056	17969.47599	5.404	17969.47537

TWO-STATE ENVIRONMENT: x = 0.80

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.000322	0.000058	17193.77563	5.529	17193.77500
20.172801	0.000319	0.000058	17300.57904	5.516	17300.57841
22.006692	0.000316	0.000058	17390.46383	5.504	17390.46320
23.840583	0.000314	0.000057	17467.15900	5.491	17467.15838
25.674474	0.000312	0.000057	17533.37266	5.479	17533.37204
27.508365	0.000311	0.000057	17591.11878	5.466	17591.11816
29.342256	0.000309	0.000057	17641.92696	5.454	17641.92634
31.176147	0.000308	0.000057	17686.97983	5.442	17686.97921
33.010038	0.000306	0.000056	17727.20288	5.429	17727.20226
34.843929	0.000305	0.000056	17763.33592	5.417	17763.33530
36.677820	0.000304	0.000056	17795.97393	5.405	17795.97331

TABLE 5. SOLUTION OF RELIABILITY INDICES FOR SINGLE GENERATOR
alpha = 0.05 mu(ss) VARIED

ONE STATE ENVIRONMENT:

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.154271	0.027579	36.25934	5.594	36.25870
20.172801	0.153713	0.027511	36.34851	5.587	36.34787
22.006692	0.153219	0.027455	36.42317	5.581	36.42253
23.840583	0.152774	0.027407	36.48659	5.574	36.48596
25.674474	0.152368	0.027366	36.54114	5.568	36.54051
27.508365	0.151994	0.027331	36.58855	5.561	36.58792
29.342256	0.151645	0.027300	36.63014	5.555	36.62951
31.176147	0.151317	0.027273	36.66692	5.548	36.66629
33.010038	0.151006	0.027248	36.69968	5.542	36.69904
34.843929	0.150711	0.027226	36.72904	5.535	36.72840
36.677820	0.150428	0.027207	36.75550	5.529	36.75487

TWO-STATE ENVIRONMENT: x = 0.20

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.154237	0.027573	36.26730	5.594	36.26666
20.172801	0.153679	0.027505	36.35644	5.587	36.35580
22.006692	0.153185	0.027449	36.43108	5.581	36.43044
23.840583	0.152741	0.027401	36.49449	5.574	36.49385
25.674474	0.152335	0.027361	36.54902	5.568	36.54838
27.508365	0.151961	0.027325	36.59642	5.561	36.59578
29.342256	0.151612	0.027294	36.63799	5.555	36.63736
31.176147	0.151284	0.027267	36.67476	5.548	36.67413
33.010038	0.150974	0.027242	36.70751	5.542	36.70688
34.843929	0.150679	0.027221	36.73686	5.535	36.73623
36.677820	0.150396	0.027201	36.76332	5.529	36.76269

TWO-STATE ENVIRONMENT: x = 0.80

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE. FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.153711	0.027479	36.39142	5.594	36.39078
20.172801	0.153158	0.027412	36.48016	5.587	36.47953
22.006692	0.152669	0.027356	36.55447	5.581	36.55383
23.840583	0.152228	0.027309	36.61759	5.574	36.61695
25.674474	0.151826	0.027269	36.67188	5.568	36.67124
27.508365	0.151454	0.027234	36.71907	5.561	36.71843
29.342256	0.151108	0.027203	36.76047	5.555	36.75984
31.176147	0.150783	0.027176	36.79708	5.548	36.79645
33.010038	0.150475	0.027152	36.82969	5.542	36.82906
34.843929	0.150182	0.027130	36.85893	5.536	36.85829
36.677820	0.149901	0.027111	36.88528	5.529	36.88465

TABLE 6. SOLUTION OF RELIABILITY INDICES FOR DUAL GENERATOR
alpha = 0.05 mu(ss) VARIED

ONE STATE ENVIRONMENT.

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.007929	0.001434	697.29171	5.529	697.29108
20.172801	0.007864	0.001426	701.46885	5.516	701.46822
22.006692	0.007807	0.001418	704.98278	5.504	704.98216
23.840583	0.007756	0.001412	707.97980	5.491	707.97918
25.674474	0.007710	0.001407	710.56612	5.478	710.56549
27.508365	0.007668	0.001403	712.82071	5.466	712.82009
29.342256	0.007629	0.001399	714.80354	5.453	714.80291
31.176147	0.007593	0.001396	716.56092	5.441	716.56030
33.010038	0.007559	0.001393	718.12922	5.429	718.12860
34.843929	0.007527	0.001390	719.53738	5.416	719.53676
36.677820	0.007497	0.001387	720.80873	5.404	720.80811

TWO-STATE ENVIRONMENT: x = 0.20

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.007929	0.001434	697.29223	5.529	697.29160
20.172801	0.007864	0.001426	701.46708	5.516	701.46645
22.006692	0.007807	0.001418	704.97909	5.504	704.97846
23.840583	0.007756	0.001412	707.97450	5.491	707.97387
25.674474	0.007710	0.001407	710.55942	5.478	710.55880
27.508365	0.007668	0.001403	712.81284	5.466	712.81221
29.342256	0.007629	0.001399	714.79463	5.453	714.79401
31.176147	0.007593	0.001396	716.55111	5.441	716.55049
33.010038	0.007559	0.001393	718.11862	5.429	718.11801
34.843929	0.007528	0.001390	719.52611	5.416	719.52549
36.677820	0.007497	0.001387	720.79685	5.404	720.79623

TWO-STATE ENVIRONMENT: x = 0.80

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.007930	0.001434	697.25629	5.529	697.25566
20.172801	0.007865	0.001426	701.39499	5.516	701.39436
22.006692	0.007808	0.001419	704.87674	5.504	704.87612
23.840583	0.007757	0.001413	707.84660	5.491	707.84597
25.674474	0.007712	0.001408	710.40969	5.478	710.40906
27.508365	0.007670	0.001403	712.64429	5.466	712.64367
29.342256	0.007631	0.001399	714.60986	5.453	714.60924
31.176147	0.007596	0.001396	716.35217	5.441	716.35155
33.010038	0.007562	0.001393	717.90728	5.429	717.90666
34.843929	0.007530	0.001390	719.30385	5.416	719.30323
36.677820	0.007500	0.001388	720.56503	5.404	720.56441

TABLE 7 SOLUTION OF RELIABILITY INDICES FOR SINGLE GENERATOR
alpha = 0.10 mu(ss) VARIED

ONE STATE ENVIRONMENT:

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.308086	0.055077	18.15648	5.594	18.15585
20.172801	0.307012	0.054949	18.19873	5.587	18.19809
22.006692	0.306059	0.054842	18.23409	5.581	18.23346
23.840583	0.305199	0.054752	18.26414	5.574	18.26350
25.674474	0.304413	0.054675	18.28998	5.568	18.28934
27.508365	0.303686	0.054608	18.31244	5.561	18.31180
29.342256	0.303007	0.054549	18.33214	5.555	18.33151
31.176147	0.302368	0.054497	18.34956	5.548	18.34893
33.010038	0.301762	0.054451	18.36508	5.542	18.36445
34.843929	0.301184	0.054410	18.37899	5.535	18.37836
36.677820	0.300631	0.054373	18.39152	5.529	18.39089

TWO-STATE ENVIRONMENT: x = 0.20

TEST PARAMETER MU(SS)	EXP DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.308006	0.055062	18.16120	5.594	18.16056
20.172801	0.306933	0.054935	18.20343	5.587	18.20280
22.006692	0.305980	0.054828	18.23879	5.581	18.23816
23.840583	0.305121	0.054738	18.26883	5.574	18.26820
25.674474	0.304335	0.054661	18.29467	5.568	18.29403
27.508365	0.303608	0.054594	18.31712	5.561	18.31649
29.342256	0.302930	0.054535	18.33682	5.555	18.33619
31.176147	0.302291	0.054483	18.35424	5.548	18.35361
33.010038	0.301685	0.054437	18.36975	5.542	18.36912
34.843929	0.301108	0.054396	18.38366	5.535	18.38303
36.677820	0.300555	0.054359	18.39619	5.529	18.39556

TWO-STATE ENVIRONMENT: x = 0.80

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.306759	0.054839	18.23505	5.594	18.23441
20.172801	0.305695	0.054713	18.27714	5.587	18.27650
22.006692	0.304751	0.054608	18.31238	5.581	18.31175
23.840583	0.303899	0.054519	18.34232	5.574	18.34168
25.674474	0.303119	0.054442	18.36807	5.568	18.36744
27.508365	0.302398	0.054376	18.39045	5.561	18.38982
29.342256	0.301725	0.054318	18.41009	5.555	18.40946
31.176147	0.301091	0.054267	18.42746	5.548	18.42682
33.010038	0.300490	0.054221	18.44292	5.542	18.44229
34.843929	0.299917	0.054181	18.45679	5.535	18.45616
36.677820	0.299367	0.054144	18.46929	5.529	18.46866

TABLE 8. SOLUTION OF RELIABILITY INDICES FOR DUAL GENERATOR
alpha = 0.10 mu(ss) VARIED

ONE STATE ENVIRONMENT:

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.031584	0.005712	175.05676	5.529	175.05613
20.172801	0.031336	0.005681	176.03945	5.516	176.03882
22.006692	0.031117	0.005654	176.86587	5.504	176.86524
23.840583	0.030923	0.005632	177.57055	5.491	177.56993
25.674474	0.030747	0.005612	178.17854	5.478	178.17792
27.508365	0.030585	0.005596	178.70846	5.466	178.70783
29.342256	0.030436	0.005581	179.17442	5.453	179.17380
31.176147	0.030297	0.005568	179.58734	5.441	179.58672
33.010038	0.030166	0.005557	179.95580	5.429	179.95518
34.843929	0.030043	0.005547	180.28659	5.416	180.28597
36.677820	0.029925	0.005538	180.58521	5.404	180.58460

TWO-STATE ENVIRONMENT: x = 0.20

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.031582	0.005712	175.07216	5.529	175.07153
20.172801	0.031333	0.005680	176.05443	5.516	176.05380
22.006692	0.031115	0.005654	176.88050	5.504	176.87987
23.840583	0.030920	0.005631	177.58488	5.491	177.58425
25.674474	0.030744	0.005612	178.19261	5.478	178.19199
27.508365	0.030583	0.005595	178.72231	5.466	178.72168
29.342256	0.030434	0.005581	179.18808	5.453	179.18746
31.176147	0.030295	0.005568	179.60084	5.441	179.60022
33.010038	0.030164	0.005557	179.96915	5.429	179.96853
34.843929	0.030041	0.005546	180.29981	5.416	180.29920
36.677820	0.029923	0.005537	180.59833	5.404	180.59771

TWO-STATE ENVIRONMENT: x = 0.80

TEST PARAMETER mu(ss)	EXP. DOWN TIME/YEAR (HOURS)	FAILURE FREQUENCY (1/YEAR)	MEAN CYCLE TIME (YEARS)	MEAN DOWN TIME (HOURS)	MEAN UP TIME (YEARS)
18.338910	0.031539	0.005704	175.30623	5.529	175.30560
20.172801	0.031293	0.005673	176.28179	5.516	176.28116
22.006692	0.031076	0.005646	177.10226	5.504	177.10163
23.840583	0.030883	0.005624	177.80191	5.491	177.80129
25.674474	0.030708	0.005605	178.40560	5.478	178.40497
27.508365	0.030547	0.005589	178.93182	5.466	178.93120
29.342256	0.030399	0.005574	179.39460	5.453	179.39398
31.176147	0.030261	0.005562	179.80474	5.441	179.80412
33.010038	0.030131	0.005550	180.17078	5.429	180.17016
34.843929	0.030008	0.005540	180.49944	5.416	180.49883
36.677820	0.029891	0.005531	180.79621	5.404	180.79559

APPENDIX

A fortran coded program for the solution of five key reliability measures follows. These measures can be solved on a repeated basis while varying a selected input parameter. Program comments provide information regarding data input. A sample data input file for the single engine, two-state environment ($\chi = 0.20$) is provided at the end of the program. Equations (1) - (7) were implemented within the program.

```
C
C      * *    CALCULATION OF RELIABILITY INDICES FDR    * *
C      * *     EMERGENCY AND STAND-BY POWER SYSTEMS     * *
C
C       *
C      FUNCTION: PROGRAM WILL PERFORM, AS DESIRED, EITHER A ONE TIME CAL-
C                CULATION OF RELIABILITY INDICES FOR A SYSTEM BASED ON DATA
C                AVAILABLE FROM THE SYSTEM'S STATE TRANSITION DIAGRAM OR WILL
C                REPETITIVELY CDMPUTE THESE INDICES WHILE VARYING A SELECTED
C                TRANSITION RATE OR COEFFICIENT OVER A SPECIFIED RANGE
C
C      DATA INPUT REQUIREMENTS:
C
C        A) FIRST DATA ENTRY IS :           (INTEGER)
C             0(ZERO) => IF ONE TIME COMPUTATION DESIRED
C             1       => IF REPEAT COMPUTATIONS DESIRED
C           NOTE(1): IF ZERO(0) IS ENTERED THEN DATA INPUT STEP(F) MUST BE
C            SKIPPED.
C        B) NUMBER OF SYSTEM STATES (INTEGER)
C        C) NUMBER OF DISTINCT TRANSITION RATES AND TRANSITION RATE
C            COEFFICIENTS (INTEGER).
C           NOTE(1):  *** << MUST COUNT 1.0 AS DISTINCT COEFFICIENT >> ***
C           NOTE(2): IF THE PROBABILISTIC COMPLEMENT OF A COEFFICIENT IS TO
C            BE USED, THE COMPLEMENT NEED NOT BE COUNTED (IT WILL BE INDICATED
C            USING A MINUS SIGN IN INPUT STEP(G)).
C        D) TOTAL NUMBER DF TRANSITIONS BETWEEN STATES (INTEGER)
C        E) DISTINCT TRANSITION RATES AND COEFFICIENTS: (i),(ii)
C             i) INPUT ORDER NUMBER (INTEGER)
C            ii) TRANSITION RATE IN UNITS OF 1/YEAR OR UNITLESS COEFFICIENT
C                (REAL).
C           NOTE(1): THE FIRST ENTRY MUST BE THE COEFFICIENT 1.0.
C        F) REPETITION CONTROL
C           IF INPUT STEP(A) IS 1, THEN ENTER: (i),(ii),(iii)
C             i) THE NUMBER OF THE PARAMETER (TRANSITION RATE OR COEFFICIENT)
C                TO BE VARIED (INTEGER)
C            ii) INCREMENT BY WHICH IT IS TO BE VARIED (REAL)
C           iii) MAXIMUM VALUE FOR PARAMETER (REAL)
C           NOTE(1): MINIMUM VALUE OF THE PARAMETER IS ENTERED AS THE VALUE IN
C            STEP(E).
C           NOTE(2): SKIP THIS STEP IF STEP(A) INPUT IS ZERO(0).
C        G) TRANSITIONS: (i),(ii),(iii),(iv),(v)
C             i) START STATE (INTEGER)
C            ii) END STATE (INTEGER)
C           iii) TRANSITION RATE NUMBER (INTEGER) - CDRRESPONDING TO NUMERICAL
C                ORDER RATES WERE ENTERED EARLIER
C            iv) FIRST COEFFICIENT NUMBER (INTEGER) - INDICATE PROBABILISTIC
C                COMPLEMENT OF COEFFICIENT BY PLACING NEGATIVE SIGN IN FRONT
C                OF THIS NUMBER.
C             V) SECOND CDEFFICIENT NUMBER (INTEGER) - INDICATE COMPLEMENT IN
C                SIMILAR MANNER
C        H) NUMBER OF FAILURE STATES (INTEGER)
C        I) LIST OF FAILURE STATES BY STATE NUMBER (INTEGERS)
C
      IMPLICIT REAL*8(A-H,O-Z), INTEGER(I-N)
      REAL*8 TRC(20), B(40,40), P(40), ZA(40,80),
     *TEMP(40), BINV(40,40)
      INTEGER FS(40), FM(40), JSTRT(100), JEND(100),
     *JTN(100), JCN1(100), JCN2(100)
      OPEN (UNIT=1, FILE='RELOUT.DAT', STATUS='NEW')
      OPEN (UNIT=2, FILE='RELIN.DAT', STATUS='OLD')
      WRITE (1,10)
   10 FORMAT (//,1X, 'SOLUTION OF RELIABILITY INDICES FOR __________',//)
C
C - - -  INITIALIZE TRANSITION RATE MATRIX (B-MATRIX)
C
      DO 20 K=1,NS
        DO 20 L=1,NS
          B(K,L) = 0.0
   20 CONTINUE
C
C - - -  READ IN DATA
C
      READ (2,*) IFLAG,NS,NTRC,NT
      READ (2,*) (M,TRC(I),I=1,NTRC)
      IF (IFLAG.EQ.1) THEN
        READ (2,*) NVAR,H,PARMAX
      ENDIF
      READ (2,*) (JSTRT(I),JEND(I),JTN(I),JCN1(I),JCN2(I),I=1,NT)
      READ (2,*) NFAIL
      READ (2,*) (FS(I),I=1,NFAIL)
C
C - - -  PRINT OUTPUT HEADER
C
      IF (IFLAG.EQ.0) THEN
      WRITE (1,23)
   23 FORMAT (2X,'EXPECTED DOWN',6X,'FAILURE',5X,3(5X,'MEAN',6X),
     */,2X,'TIME PER YEAR',5X,'FREQUENCY',6X,'CYCLE TIME',6X,
     *'DOWN TIME',7X,'UP TIME',/,4X,'( HOURS )',8X,'(1/YEAR)',4X,
     *3X,'( YEARS )',3X,3X,'( HOURS )',3X,3X,'( YEARS )',3X,
     */,80('-'),//)
        ELSE
      WRITE (1,27)
   27 FORMAT (5X,'TEST',7X,'EXP. DOWN',6X,'FAILURE',3X,
     *3(4X,'MEAN',5X),/,3X,'PARAMETER',4X,'TIME/YEAR',5X,
     *'FREQUENCY',3X,'CYCLE TIME',4X,'DOWN TIME',4X,'UP TIME',
```

```
     •/,16X,'( HOURS )',6X,'(1/YEAR)',2X,2X,'( YEARS )',2X,
     •2X,'( HOURS )',2X,2X,'( YEARS )',2X,/,80('-'),//)
      ENDIF
C
C - - -  FORMULATION OF TRANSITION RATE MATRIX (B-MATRIX)
C
   30 DO 35 I=1,NT
        IF (JCN1(I).LT.0) THEN
            JCMPL = -JCN1(I)
            COEFF1 = 1.0 - TRC(JCMPL)
          ELSE
            COEFF1 = TRC(JCN1(I))
        ENDIF
        IF (JCN2(I).LT.0) THEN
            JCMPL = -JCN2(I)
            COEFF2 = 1.0 - TRC(JCMPL)
          ELSE
            COEFF2 = TRC(JCN2(I))
        ENDIF
        B(JEND(I),JSTRT(I)) = TRC(JTN(I)) • COEFF1 • COEFF2
   35 CONTINUE
      DO 40 I=1,NS
        B(I,I) = 0.0
        DO 40 J=1,NS
          IF (I.EQ.J) GOTO 40
          B(I,I) = B(I,I) - B(J,I)
   40 CONTINUE
C
C ( SAVE ROW 1 IN TEMPORARY ARRAY )
C
      DO 50 I=1,NS
        TEMP(I) = B(1,I)
        B(1,I) = 1.0
   50 CONTINUE
C
C - - -  INVERT B-MATRIX
C
      NP = NS + NS
      CALL MATINV(NS,NP,B,BINV,ZA)
C
C - - -  COMPUTATION OF STEADY STATE PROBABILITY VECTOR (R-VECTOR)
C
      DO 60 I=1,NS
        P(I) = BINV(I,1)
   60 CONTINUE
C
C - - -  RESTORE ORIGINAL TRANSITION RATE MATRIX (B-MATRIX)
C
      DO 70 I=1,NS
        B(1,I) = TEMP(I)
   70 CONTINUE
C
C-------------------------------------------------------------------------------
C
C   ••• COMPUTATION OF RELIABILITY INDICES •••
C
C - - -  FORMULATION OF FAILURE MODE VECTOR (FM-VECTOR)
C
      YTH = 8766.0
      DO 80 I=1,NS
        FM(I) = 0
   80 CONTINUE
      DO 90 I=1,NFAIL
        K = FS(I)
        FM(K) = 1
   90 CONTINUE
C
C - - -<<< EXPECTED DOWN TIME PER YEAR (HOURS) >>>
C
      PF = 0.0
      DO 100 I=1,NS
        IF (FM(I).EQ.1) THEN
          PF = PF + P(I)
        ENDIF
  100 CONTINUE
C
C - - -<<< FAILURE FREQUENCY OF SYSTEM (FF) >>>
C
      FF = 0.0
      DO 120 I=1,NS
        IF (FM(I).EQ.0) THEN
        SUM = 0.0
        DO 110 J=1,NS
          IF (FM(J).EQ.1) THEN
          SUM = SUM + B(J,I)
          ENDIF
  110   CONTINUE
        FF = FF + P(I)•SUM
        ENDIF
  120 CONTINUE
C
C - - -<<< MEAN CYCLE TIME (TF) / MEAN DOWN TIME (DF) / MEAN UP TIME (DU) >>>
C
      TF = 1.0/FF
      DF = PF/FF
```

```
     DU = TF - DF
C
C--------------------------------------------------------------------------------------------------
C
C  ** OUTPUT **
C
     PF = PF*YTH
CCC     TF = TF*YTH
     DF = DF*YTH
CCC     DU = DU*YTH
     IF (IFLAG.EQ.1) THEN
        WRITE (1,130) TRC(NVAR),PF,FF,TF,DF,DU
  130    FORMAT (1X,3F13.6,F13.5,F13.3,F13.5)
        IF (TRC(NVAR).LT.PARMAX) THEN
          TRC(NVAR) = TRC(NVAR) + H
          GOTO 30
        ENDIF
      ELSE
        WRITE (1,140) PF,FF,TF,DF,DU
  140    FORMAT (1X,2F16.6,F15.5,F13.3,F13.5)
     ENDIF
     STOP
     END
C
C--------------------------------------------------------------------------------------------
C
      SUBROUTINE MATINV(N,NP,A,AI,ZA)
C
C  NOTE:        N = DIMENSION OF MATRIX TO BE INVERTED ( LESS THAN OR
C                   EQUAL TO DIMENSION OF MATRIX AS SPECIFIED IN THE
C                   DIMENSION STATEMENT OF THE CALLING PROGRAM )
C
C            NP = 2 * N
C
C             A = MATRIX TO BE INVERTED
C
C            AI = INVERTED MATRIX
C
C            ZA = DUMMY ARRAY
C
      REAL*8 A(40,40),ZA(40,80),AI(40,40)
      REAL*8 ALFA,BETA
      DO 26 I=1,N
      DO 24 J=1,N
      ZA(I,J) = A(I,J)
      NJ = N + J
24     ZA(I,NJ) = 0.0
      NI = N + I
26     ZA(I,NI) = 1.0
      DO 111 IR = 1,N
      IF (DABS(ZA(IR,IR)).LT.1.E-20)THEN
      DO IROW=1,N
      IF(DABS(ZA(IROW,IR)).GE.1.E-20)THEN
      DO IC = 1,NP
      ZA(IR,IC) = ZA(IR,IC) + ZA(IROW,IC)
      END DO
      GO TO 111
      END IF
      END DO
      GO TO 35
      END IF
111     CONTINUE
C
C  **** SET MAIN DIAGONAL ELEMENT TO UNITY AFTER
C  **** TESTING FOR ZERO VALUE
C
      DO 12 I=1,N
      ALPHA = ZA(I,I)
C      IF(DABS(ALPHA).LT.1.E-20)GO TO 35
      DO 5 J=1,NP
5      ZA(I,J) = ZA(I,J)/ALPHA
C
C  **** SET THE ELEMENTS OF THE ITH COLUMN TO ZERO
C
      DO 11 K=1,N
      IF (K-I)8,11,8
8      BETA = ZA(K,I)
      DO 10 J=I,NP
10     ZA(K,J) = ZA(K,J) - BETA * ZA(I,J)
11     CONTINUE
12     CONTINUE
      DO 33 J=1,N
      JN = J + N
      DO 33 I=1,N
33     AI(I,J) = ZA(I,JN)
      RETURN
C
C  **** PRINT ERROR MESSAGE IF METHOD FAILS
35     PRINT *,'****>   MAIN DIAGONAL ELEMENT IS ZERO ****>'
      RETURN
      END
```

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